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A STUDY OF THE EFFECT OF AFTERCOOLING ON THE POWER  
AND THE WEIGHT OF A 2000-HORSEPOWER  
AIR-COOLED ENGINE INSTALLATION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Materiel Command

A STUDY OF THE EFFECT OF AFTERCOOLING ON THE POWER  
AND THE WEIGHT OF A 2000-HORSEPOWER  
AIR-COOLED ENGINE INSTALLATION

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SUMMARY

A study is made of the effect of aftercooling on the brake horsepower, the weight, and the weight-power ratio of a power plant consisting of a 2000-horsepower air-cooled engine, an intercooler, and two stages of supercharging. The study is for full-throttle operation at 30,000 feet. The dependence of brake horsepower on supercharger performance is stressed. Three cases are considered: (1) inadequate supercharging, (2) supercharging to constant manifold pressure, and (3) supercharging to detonation-limited manifold pressure.

With inadequate supercharging, little gain in brake horsepower results from aftercooling. With proper superchargers, strengthened engine parts, and increased engine-cooling-fin area, an increase of 42 percent in brake horsepower is shown for operation at constant manifold pressure and aftercooling to a manifold temperature of 40° F. For operation at detonation-limited manifold pressures, the increase in brake horsepower shown here is 42 percent for aftercooling to a manifold temperature of 100° F, and 67 percent for aftercooling to a manifold temperature of 40° F.

Aftercooling can produce some reduction in the weight-power ratio of the power plant. The maximum reduction shown herein is 10 percent, which is for operation at detonation-limited manifold pressure and for aftercooling to a manifold temperature of 80° F to 100° F. The greatest reduction shown for aftercooling to 40° F is 6 percent.

Some of the difficulties connected with aftercooling are mentioned.

## INTRODUCTION

There is always considerable interest in the performance of aircraft power-plant induction systems. Various components of induction systems have been considered in many reports issued by the industry and by the National Advisory Committee for Aeronautics. Among these reports are a few in which aftercooling has been considered. Reference 1 has a discussion of the relative merits of aftercooling and intercooling, with special emphasis on difficulties of installation. Reference 2 presents a discussion of charge-cooling methods, one of which is aftercooling, and points out a fact that is quantitatively treated in the present report; namely, that "the supercharger characteristics must be carefully matched to the other components of the installation in order to meet engine requirements."

Little quantitative treatment of aftercooling has appeared in the literature. In the present report, calculated results are presented to emphasize the effect of supercharger performance on the increase in brake horsepower that can be obtained by means of aftercooling, and to show the effect of aftercooling on the weight and the weight-power ratio of the power plant. Although the results given here are quantitatively applicable to one power plant operating under given conditions, they are qualitatively applicable to other power plants.

A true evaluation of the merits and the demerits of aftercooling must take into account a number of factors. The treatment of supercharger performance and power-plant weight given here will facilitate a better understanding and a better appraisal of aftercooling.

## CONDITIONS USED IN CALCULATIONS

For the present study an aircooled engine that develops 2445 indicated horsepower with wide-open throttle and with a manifold temperature of  $233^{\circ}\text{F}$  and a manifold pressure of 50 inches mercury was chosen as the reference engine. The induction system of the engine consists of an exhaust-turbine-driven auxiliary supercharger, an intercooler that reduces the charge-air temperature to  $100^{\circ}\text{F}$ , a carburetor, and a gear-driven main-stage supercharger. In the NACA standard atmosphere at 30,000 feet altitude with 3 inches mercury ram (450 mph), the charge in the intake manifold has the temperature and the pressure mentioned above, and the engine develops 2445 indicated horsepower and 2000 brake horsepower.

Aftercoolers of the air-to-air type that reduce the manifold temperature of the charge are assumed to be installed in the induction system following the main-stage supercharger. When the charge is cooled by an aftercooler, the density of the charge, the weight rate of flow of charge, and the indicated engine power are changed. In the following sections the effects of aftercooling to various manifold temperatures on indicated horsepower, brake horsepower, and power-plant weight are determined under various conditions of supercharger performance for flight at 30,000 feet. A more detailed list of the conditions used in the calculations is given in the appendix.

## RESULTS AND DISCUSSION

### Aftercooling with Inadequate Superchargers

In the present section, in which aftercooling with inadequate supercharging is considered, performance charts for the auxiliary and the main-stage superchargers are assumed. These charts are shown in figure 1. For the reference condition of no aftercooling, for which the manifold temperature is  $233^{\circ}\text{F}$ , the superchargers operate near the peak of the constant-speed contour of 340 rps, as is shown. As the manifold temperature is lowered, the volume rate of flow  $Q$  through the superchargers increases, and the adiabatic work per pound of fluid falls off along

the 340 rps curve as shown. (It is assumed that the superchargers cannot be operated at greater speed than 340 rps.) The resulting decrease in the pressure ratios across the superchargers is shown in figure 2, as is the decrease in manifold pressure. The indicated horsepower and the brake horsepower are also shown in figure 2. The indicated horsepower is proportional to the weight rate of flow of charge. The brake horsepower is computed as indicated horsepower less friction horsepower less main-stage horsepower. The friction horsepower is taken as constant at 175. The main-stage horsepower is shown in figure 3. The maximum gain in brake horsepower that is obtained by aftercooling is about 200. Although the performance of the superchargers is quite good for the reference condition of no aftercooling, their performance is inadequate for obtaining much increase in engine power by means of aftercooling.

In figure 3 is plotted the aftercooler weight. Throughout the present paper "aftercooler weight" includes the weight of the air-to-air heat exchanger itself, the weight of the associated supports and ducting, and the weight of the cooling-air scoop.

One standard for measuring the performance of an aircraft power plant is the ratio of power-plant weight to brake horsepower. In the present case the power-plant weight, shown in figure 3, is the weight of the reference power plant, 3400 pounds, plus the aftercooler weight. The weight-power ratio is also shown in figure 3. Without aftercooling, the ratio is 1.70 pounds per horsepower. Aftercooling to 150° F lowers the ratio slightly to a minimum of 1.66.

#### Aftercooling with Constant Manifold Pressure

If the auxiliary and the main-stage superchargers can be designed, for each degree of aftercooling, to handle at constant pressure ratio the increased rate of flow that results from aftercooling, the gain in brake horsepower that results from aftercooling will be greater than that shown in figure 2. Figures 4 to 7 show the pertinent powers and weights as functions of manifold temperature when the supercharger pressure ratios and efficiencies are held constant at the values they have in the reference power plant, and the manifold pressure consequently is constant at 50 inches mercury.

In figure 4 is shown the indicated horsepower. In figure 5 is shown the main-stage supercharger power and the brake power. As before, the brake horsepower is the indicated horsepower minus the friction horsepower (175) minus the main-stage horsepower. The brake horsepower is increased, by aftercooling to  $40^{\circ}$  F at constant manifold pressure, from 2000 to 2860.

The gain in brake horsepower shown in figure 5 is made, however, at the expense of considerable increase in the weight of the power plant. In figure 6 are shown the changes in the weights of the various components of the power plant. The weights of the auxiliary supercharger and the main-stage supercharger were increased over the weights of the original, or reference, installation linearly with the increase in weight rate of charge flow, as manifold temperature was decreased. The weights of the intercooler and the aftercooler were determined on the bases of required rate of heat dissipation, existing temperature difference, and reasonable cooling-air pressure drop and rate of flow. In order that a constant percentage of the indicated power could be dissipated to the cooling air at constant cooling-air pressure drop, the width and the weight of the engine-cooling fins were increased linearly with indicated power. (The assumption is accordingly made that the fin effectiveness is not a function of the fin width. The assumption, although inaccurate, is justified by the fact that the total fin weight is a very small portion of the total power-plant weight.)

The large increase in indicated horsepower that results from aftercooling - an increase from 2145 horsepower for the reference condition of  $233^{\circ}$  F manifold temperature to 3385 horsepower for a  $40^{\circ}$  manifold temperature - would lower the safety factor of the stressed parts of the engine considerably, unless these parts were strengthened. It is believed that the weights of only the cylinder walls, the cylinder heads, and the connecting rods need be appreciably increased. The calculated increases in the required weights of these parts are given in figure 6. The increases were calculated on the basis of the maximum combustion pressures developed in the cylinders. The maximum pressures were obtained by means of a Mollier chart. The use of such a chart to obtain maximum cylinder pressures does not give accurate results, as is well known. It is assumed here, however, that for the present purpose the accuracy is sufficient.

The values obtained for the maximum pressures were used in the conventional text-book design formulas to obtain the necessary cylinder-wall and cylinder-head thickness and connecting-rod cross section for constant factors of safety. Although text-book design equations have limited value for designing an engine from scratch, they give sufficiently accurate results when used for computing small differences in weight.

Figure 7 gives the total weight of the power plant as a function of manifold temperature. The power-plant weight-power ratio is also shown in figure 7. The weight-power ratio is shown here in order to obtain some insight into the question of which is fundamentally the better method of increasing brake horsepower, by aftercooling or by increasing the number of engine cylinders. As a criterion, the weight-power ratio is not perfect, as in itself it gives no indication of the relative difficulties involved in installing an additional heat exchanger in an airplane and in increasing the number of cylinders. The weight-power ratio shown in figure 7 is seen to be reduced from a value of 1.70 for no aftercooling to a minimum of 1.59 for a manifold temperature of 90° F.

#### Aftercooling with Detonation-Limited Manifold Pressure

The effects of charge cooling, shown above, on brake horsepower and power-plant weight, with manifold pressure both decreasing and constant as manifold temperature is lowered, lead naturally to the question of the effect when the manifold pressure is raised as the manifold temperature is lowered. If the reference manifold pressure of 50 inches mercury is taken as the detonation-limited pressure for a manifold temperature of 233° F, then, as the manifold temperature is lowered by aftercooling, the manifold pressure can be raised for the same detonation.

The question of the most advisable relation between detonation-limited manifold pressure and manifold temperature for use in the present study is one that is difficult to decide. Some fifteen reports on the subject have been read by the authors. In terms of the required temperature drop per inch of mercury increase in pressure, the reported results range from more than 40° F per inch mercury to 5° F per inch mercury. Furthermore, it has been shown that curves of allowable pressure plotted against

temperature go through maxima at various temperatures. It is clear that, with the wide variation among published results, the relation between allowable pressure and temperature is a function of several factors that have not yet been evaluated. The present authors have decided to assume that each  $20^{\circ}$  drop in temperature permits a 1-inch increase in pressure. The use of this relation can be defended on the grounds that it represents a kind of rough average of the published results, and that it is probably not unconservative. This relation permits an increase in manifold pressure from the reference pressure of 50 inches mercury at a temperature of  $233^{\circ}$  F to 59.7 inches mercury at a temperature of  $40^{\circ}$  F.

The indicated horsepower for fixed detonation is plotted in figure 8. (The ordinate scale used in figure 8 is different from that used in all the other plots of power in this report.) The power required for the operation of the geared main-stage supercharger and the pressure ratios of the two superchargers are also shown in figure 8. The efficiency of the superchargers is held constant at 65 percent. The brake horsepower delivered by the engine is given in figure 9. Here again the friction horsepower is taken as constant, inasmuch as an acceptable relation between indicated horsepower and friction horsepower at constant engine speed could not be found. Quite a large increase in brake horsepower is shown in figure 9 - from 2000 to 2850 horsepower, or 42 percent, for aftercooling to  $100^{\circ}$  F, and from 2000 to 3350 horsepower, or 67 percent, for aftercooling to  $40^{\circ}$  F.

In figure 10 are shown the manifold pressure, the calculated changes in the weights of the cylinders and the connecting rods, which changes are based on the maximum combustion pressures developed in the cylinders, the weights of the auxiliary and the main-stage superchargers, the weights of the intercooler and the aftercooler installations, and the increase in the weight of the fins.

In figure 11 is shown the total weight of the power plant. The power-plant weight increases rapidly as the manifold temperature approaches  $40^{\circ}$  F, principally on account of the rapid increase in aftercooler weight. The rapid increase in aftercooler weight is due to the fact that, as manifold temperature approaches  $40^{\circ}$  F, the heat-transfer demands made of the aftercooler become severe. As the manifold temperature is lowered, the outlet temperature from the aftercooler approaches the inlet

temperature of the cooling air. Furthermore, the rate of heat transfer required of the aftercooler increases for three reasons: the temperature of the charge air at the aftercooler outlet decreases, the rate of flow of charge air increases, and, on account of the rise in the pressure ratio of the main-stage supercharger, the temperature of the charge air at the aftercooler inlet increases.

The weight-brake-horsepower ratio of the power plant is also shown in figure 11. The weight-power ratio is more favorable than for the two cases previously considered in this paper. In this case it decreases from 1.70, for no aftercooling, to a minimum of 1.53, for a manifold temperature of 80° F to 100° F. The minimum represents a decrease of 10 percent in the value of the ratio. The ratio has a value of 1.6 (a 6-percent decrease) for the lowest manifold temperature shown (40° F), at which temperature the gain in brake horsepower is greatest.

#### Summarized Results

The results of the present report are summarized in figures 12 and 13. Figure 12 shows the variation of brake horsepower with manifold temperature for the three cases of aftercooling considered above; namely, (1) with the original superchargers, which are inadequate when aftercooling is used, (2) with the capacity of the superchargers increased to give constant manifold pressure, and (3) with the capacity and the pressure ratio of the superchargers increased to give detonation-limited engine operation. The figure shows how largely the power gain that is possible with aftercooling is contingent upon proper supercharging.

Figure 13 shows the variation with manifold temperature of the weight-power ratio of the power plant for the three cases.

#### OTHER ASPECTS OF THE AFTERCOOLING PROBLEM

A number of other aspects of the problem of aftercooling must be mentioned. It should be noted that the results of the present report, which are for wide-open-throttle operation, are applicable to fighter-type

airplanes, for which maximum brake horsepower is important, but are not pertinent for cargo-type airplanes, almost the entire operation of which is at part throttle.

The "aftercooler weight" used in this report is for air-to-air heat exchangers. In radial engines of current design, the main-stage supercharger is integral with the engine, and nine charge-inlet pipes are used between the main-stage supercharger and the cylinders. The installation of air-to-air heat exchangers - one on each of the nine pipes - is practically an impossibility, on account of space limitations and ducting problems. The use of liquid-to-air-to-liquid aftercoolers would to some extent alleviate the installation problem, but would result in somewhat higher aftercooler weights than those shown here. The results given here, therefore, are pertinent as partial answer to the question of whether or not the benefits to be derived from aftercooling are great enough for it to be logical for the engine designer to try to redesign the induction system of radial engines in such a way that air-to-air aftercoolers could be installed.

One quantity that is not shown by the figures of the present report is the drag power of the cooling air that is used in the aftercoolers. This drag power, which might logically be subtracted from the brake horsepower shown in the figures, has been calculated for all cases. It is not shown, however, as for most of the aftercooler outlet temperatures it is quite small, and would make no significant difference in the results. Its largest value is for the case of aftercooling to 40° F manifold temperature with detonation-limited manifold pressure; that is, at the left-hand side of figure 9. Even for that condition, however, and when increased by taking into account an 80-percent duct efficiency and also an 80-percent propeller efficiency, its value does not exceed 50 horsepower.

The maximum value of the drag power of the inter-cooler cooling air is likewise less than 50 horsepower.

In order to simplify the calculation of the engine-fin weight, the assumptions were made that the engine cooling-air pressure drop was held constant, and that the additional required fin surface area was obtained by increasing the width of the fins. Under these assumptions, the engine cooling-air drag power is proportional to the indicated engine power. As was shown in reference 3, the cooling-air drag power for an engine with well-designed

fins is of the order of 4 percent of the engine indicated power, or about 100 horsepower for a 2000-brake-horsepower engine. The maximum change in indicated power shown in the present paper is an increase from 2445 horsepower to 4040 horsepower. The maximum increase in engine cooling-air drag power is consequently of the order of 65 horsepower. On the other hand, if fin width was increased on an actual engine, at the same time fin spacing would probably be decreased. The pressure drop required would, in general, then be decreased, and the maximum increase in drag power would consequently be less than 65 horsepower.

The possibility of condensation of the fuel in the intake manifold should also be mentioned. The occurrence of condensation depends largely on the quality of the fuel and the temperature of the charge. Condensation, which might well take place at the lower values of manifold temperature shown in this report, results in reduction of the effective fuel-air ratio and in the formation of carbon deposits in the engine.

The authors are well aware of the fact that the additional fin surface area required for proper cooling of the engine at the high engine powers shown herein is not easy to obtain. They also realize that redesigning the stressed engine parts for the high cylinder pressures that aftercooling makes possible is a major problem, that increasing the volume capacity and the pressure ratios of the superchargers may be quite difficult, and that the aftercoolers must be of sufficient strength to resist the pressure caused by backfire.

### CONCLUSIONS

The following conclusions can be drawn from the present study:

1. The gain in engine brake horsepower that can be obtained by means of installing aftercoolers in existing power plants is largely dependent upon the performance of the superchargers. If the supercharger pressure ratios fall off when the rate of charge flow is increased by aftercooling, then aftercooling results in little gain in power.

2. Aftercooling, in combination with proper superchargers, strengthened engine parts, and increased cylinder-fin area, can give a large increase in brake horsepower. The increase shown here for operation at constant manifold pressure is 42 percent at a manifold temperature of 40° F. The increase shown here for operation at detonation-limited manifold pressures is 42 percent for aftercooling to a manifold temperature of 100° F, and 67 percent for aftercooling to a manifold temperature of 40° F.

3. Aftercooling can result in some reduction in the weight-power ratio of the power plant. The present report shows a maximum reduction of 10 percent, which is for detonation-limited operation and manifold temperature of 80° F to 100° F. If the manifold temperature is lowered further to 40° F, for greater horsepower gain, the reduction in weight-power ratio shown here is 6 percent.

Langley Memorial Aeronautical Laboratory  
National Advisory Committee for Aeronautics  
Langley Field, Va., September 16, 1944

## APPENDIX

## CONDITIONS USED IN CALCULATIONS

The following conditions were used in making the calculations for the present report. Reasonable changes in most of these conditions would have no qualitative effect and little quantitative effect on the results that have been obtained.

1. The reference power plant for which the analyses were made operates at an altitude of 30,000 feet in NACA standard air with 3 inches mercury ram (450 mph).
2. The engine in the reference power plant develops 2445 indicated horsepower and 2000 brake horsepower at full throttle at 30,000 feet with a manifold pressure of 50 inches mercury and a manifold temperature of 233° F.
3. Only full-throttle engine operation is considered.
4. Engine rpm, spark setting, valve timing, and fuel-air ratio are constant. As useful approximations, indicated specific air consumption and cylinder volumetric efficiency are considered as constant (reference 4). (Inasmuch as the present calculations are for a fixed altitude, cylinder volumetric efficiency may be based either on atmospheric pressure and temperature, or, as in reference 4, on manifold pressure and temperature.) Engine indicated horsepower is therefore considered to be proportional to weight rate of flow of charge, and weight rate of flow is proportional to manifold density.
5. Engine friction power is constant at 175 horsepower.
6. The effect of water injection into the charge is not considered.
7. The pressure drop across the carburetor is 0.5 inch mercury.
8. The pressure drop of the charge air across all aftercoolers is fixed at 0.5 inch mercury, across all intercoolers at 1 inch mercury, and in the ducting at 0.75 inch mercury.

9. All intercoolers lower the temperature of the charge air to 100° F.

10. Intercoolers and aftercoolers are calculated on the basis of Army summer air temperature.

11. The fuel is completely vaporized in the carburetor.

12. The air consumption of the engine is 1.72 pounds per second per thousand indicated horsepower.

13. The weight of the propeller is not included in the weight of the power plant.

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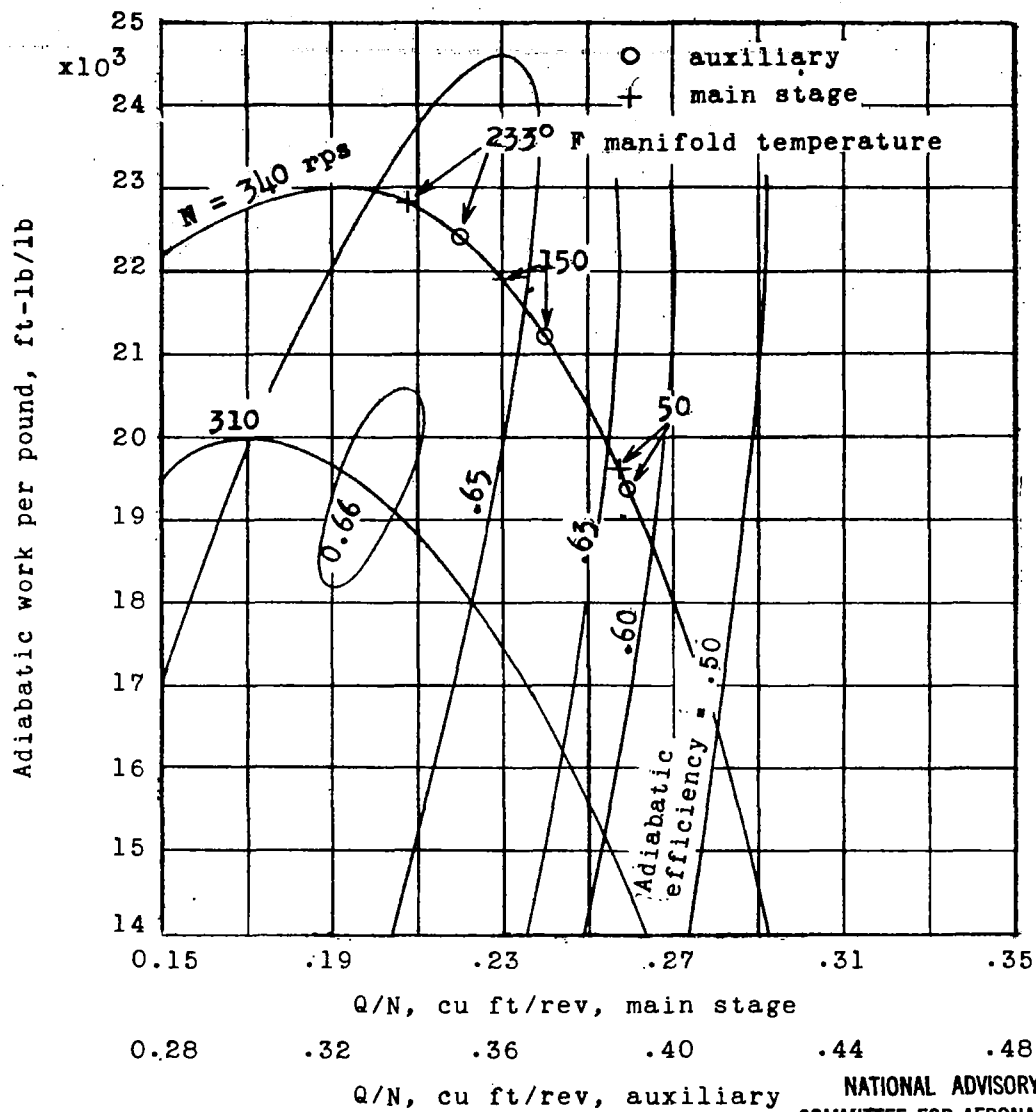


Figure 1.- Supercharger performance charts. Adiabatic work per pound as a function of inlet volume per revolution,  $Q/N$ , and adiabatic efficiency.

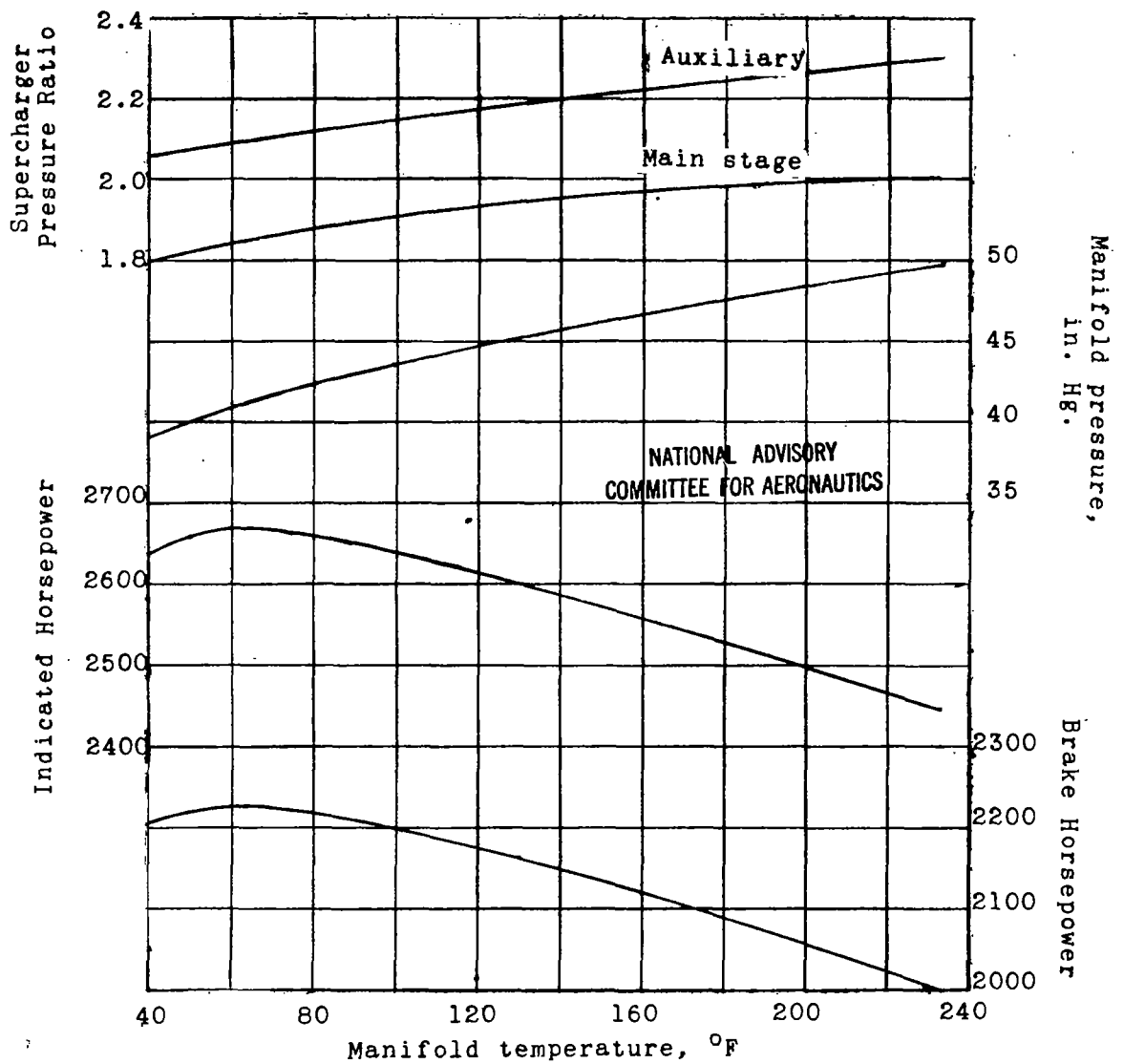


Figure 2.- Supercharger pressure ratios, manifold pressure, indicated horsepower, and brake horsepower as functions of manifold temperature. Inadequate supercharging.

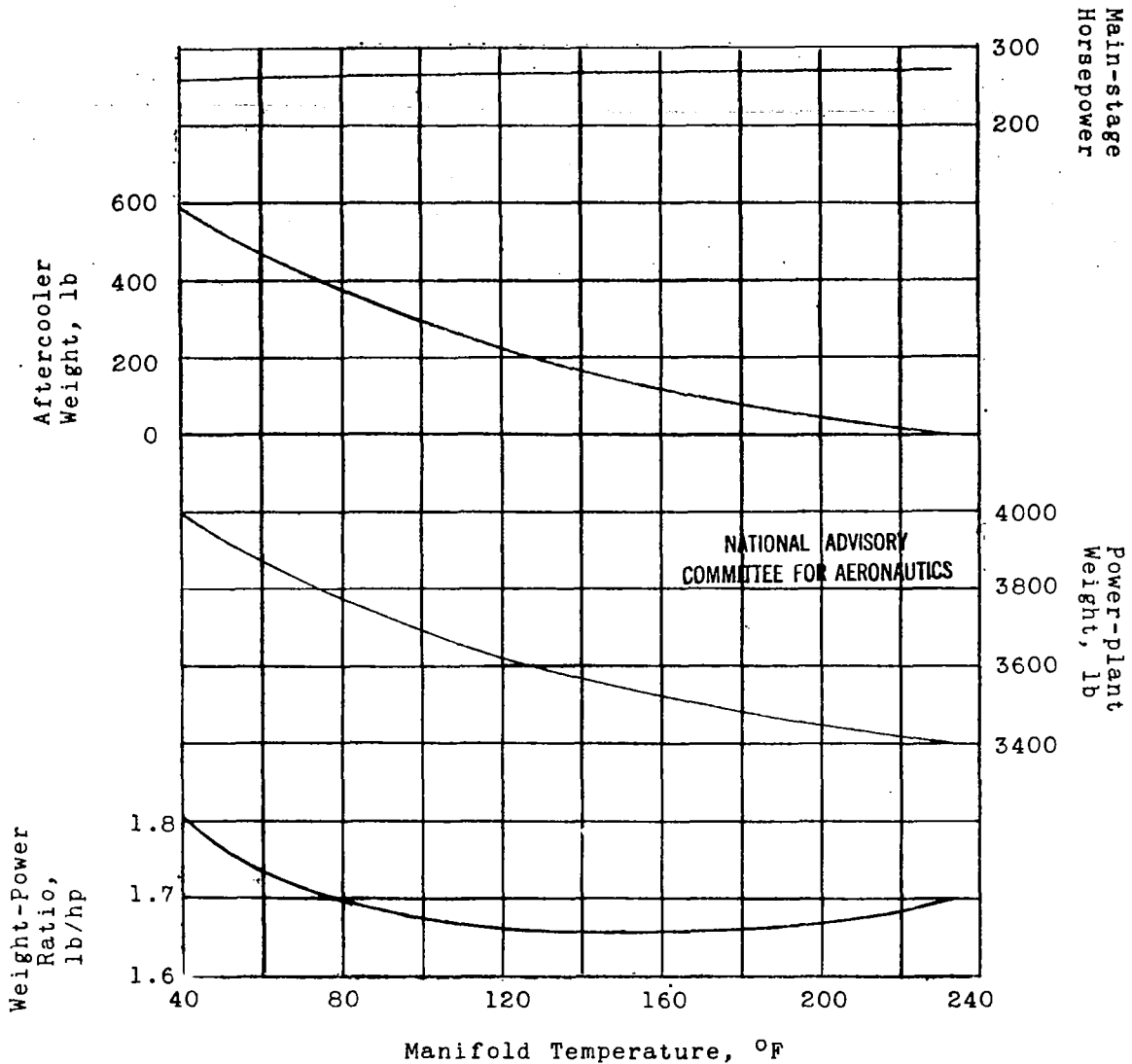


Figure 3.- Main-stage supercharger power, aftercooler weight, power-plant weight, and power-plant weight-power ratio as functions of manifold temperature. Inadequate supercharging.

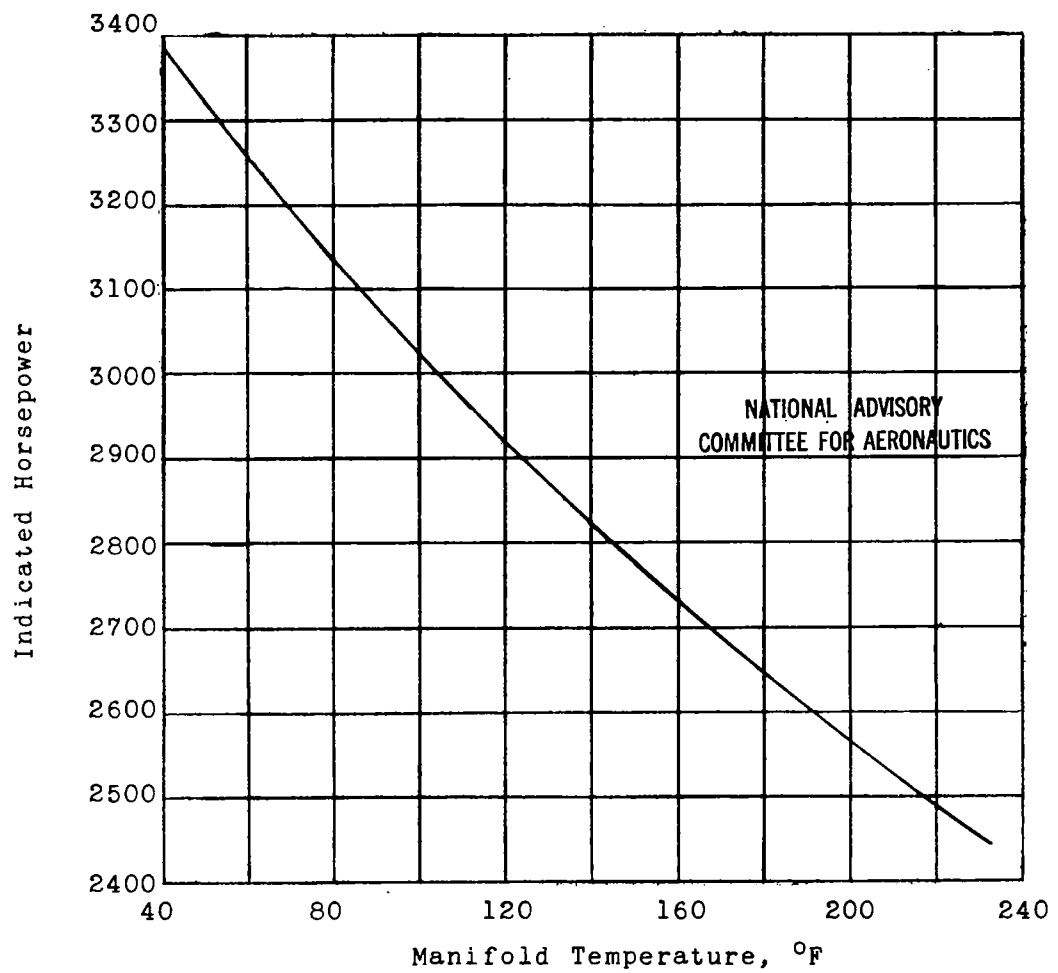


Figure 4.- Indicated horsepower as a function of manifold temperature. Constant manifold pressure.

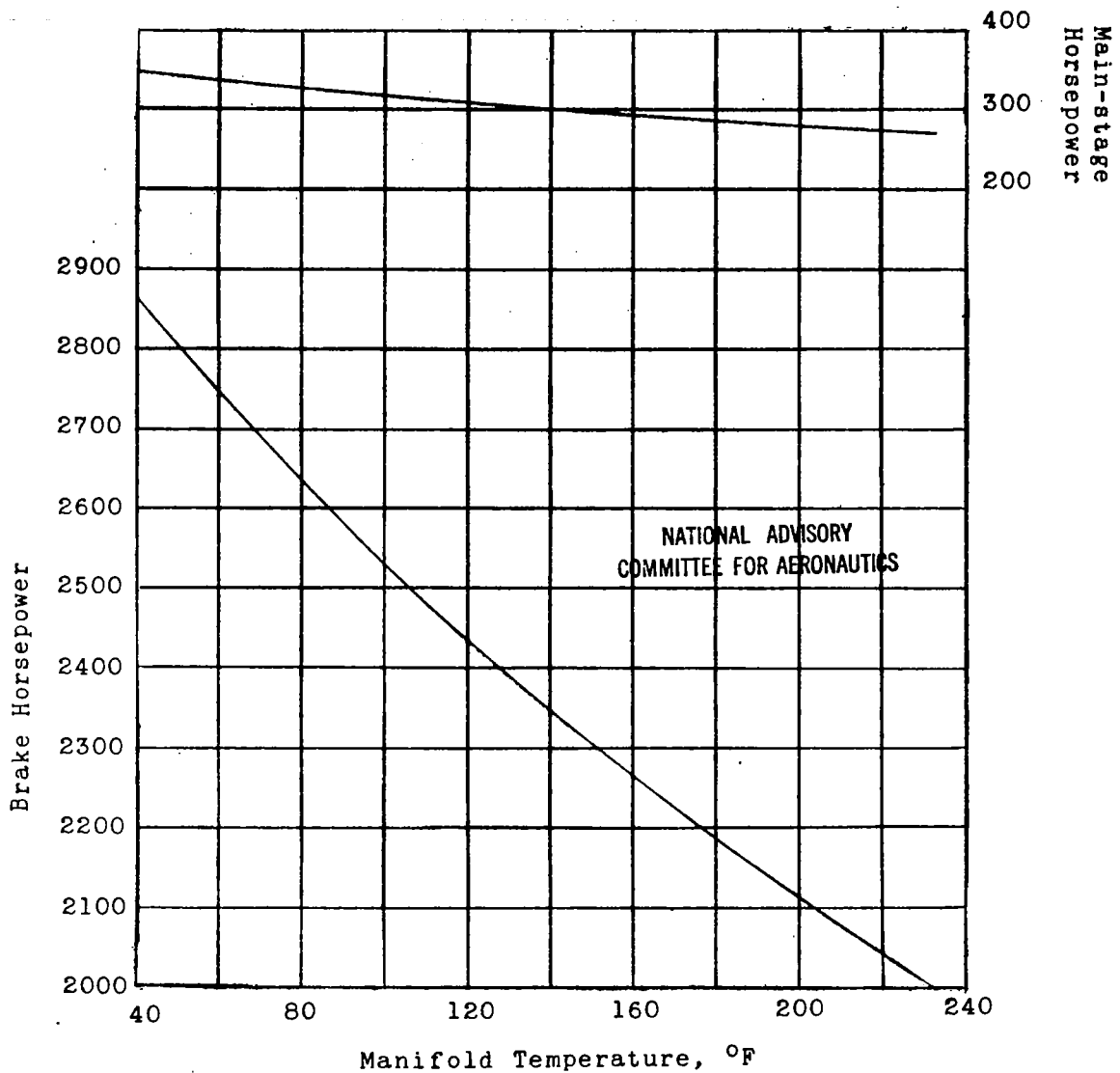


Figure 5.- Main-stage supercharger power and brake horsepower as functions of manifold temperature. Constant manifold pressure.

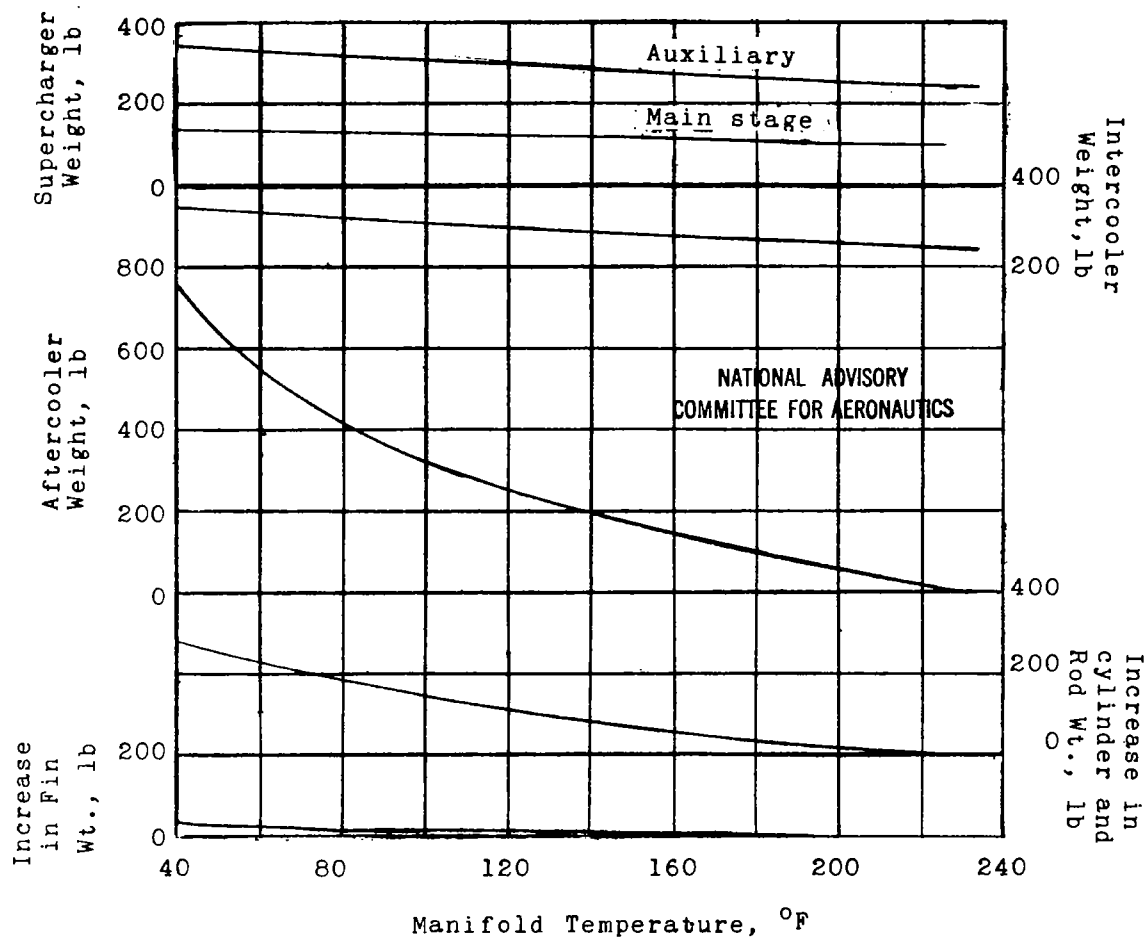


Figure 6.- Effect of manifold temperature on required weight of various power-plant components. Constant manifold pressure.

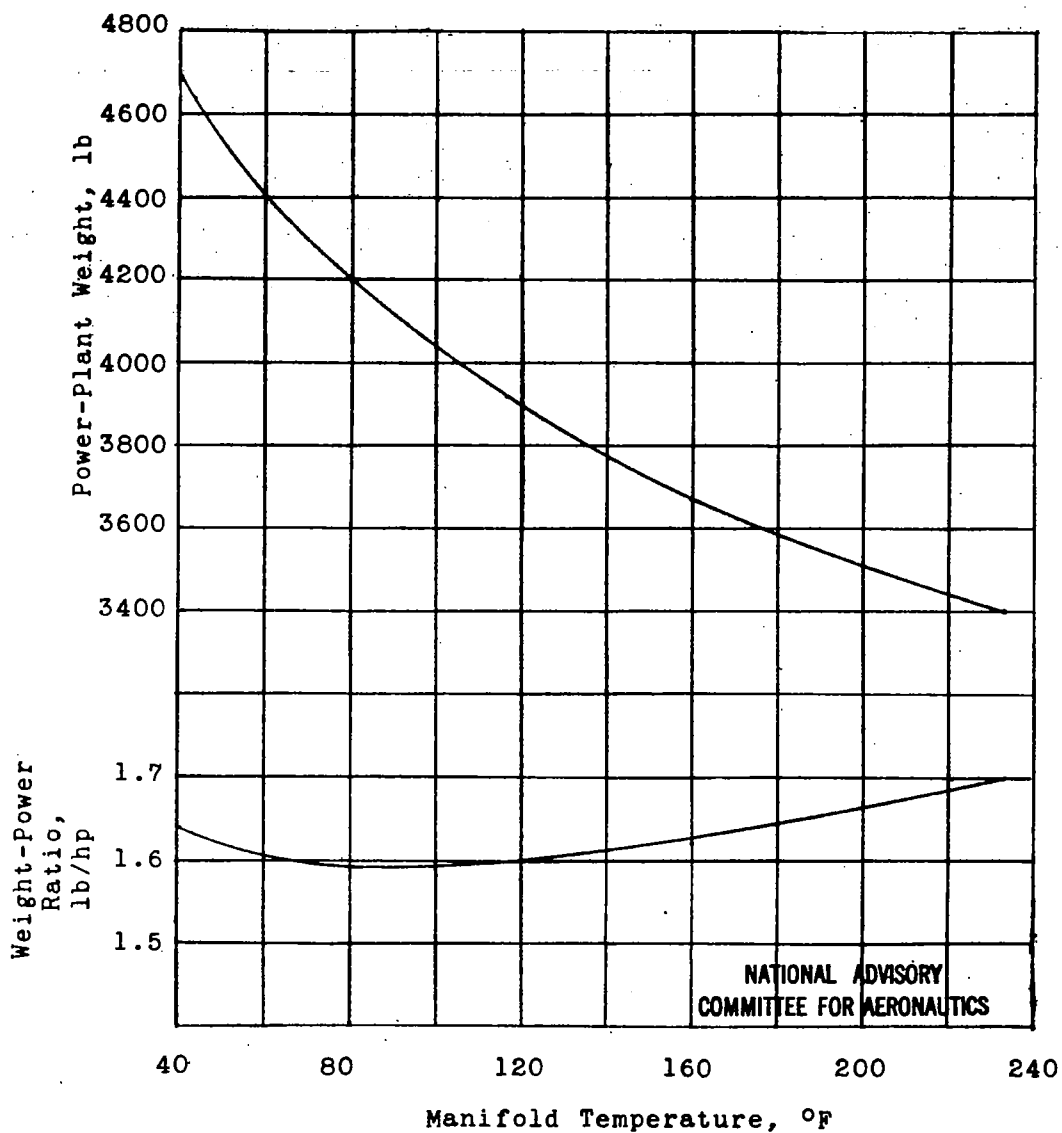


Figure 7.- Power-plant weight and weight-power ratio as functions of manifold temperature. Constant manifold pressure.

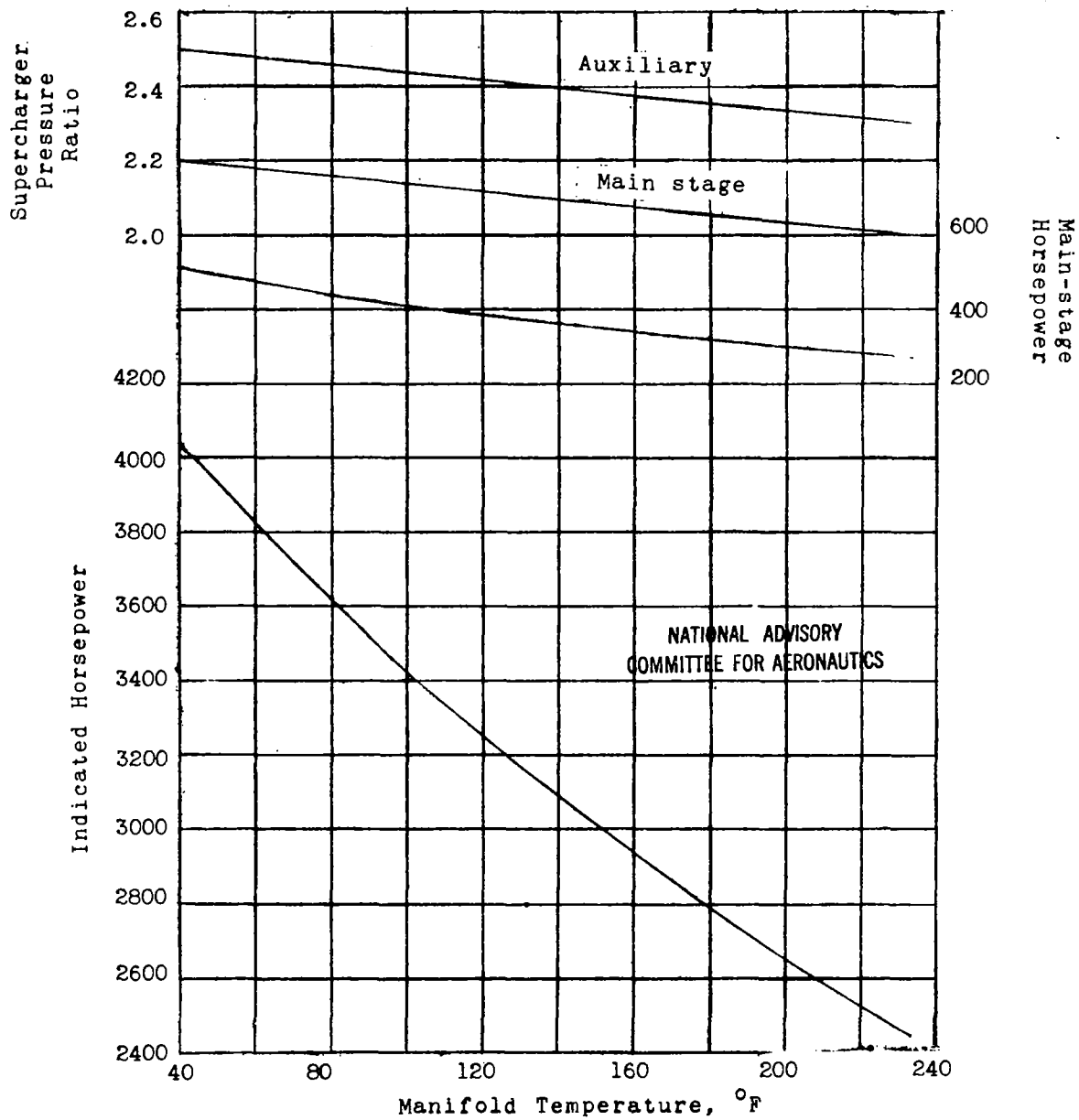


Figure 8.- Supercharger pressure ratios, main-stage supercharger power, and indicated horsepower as functions of manifold temperature. Detonation-limited manifold pressure.

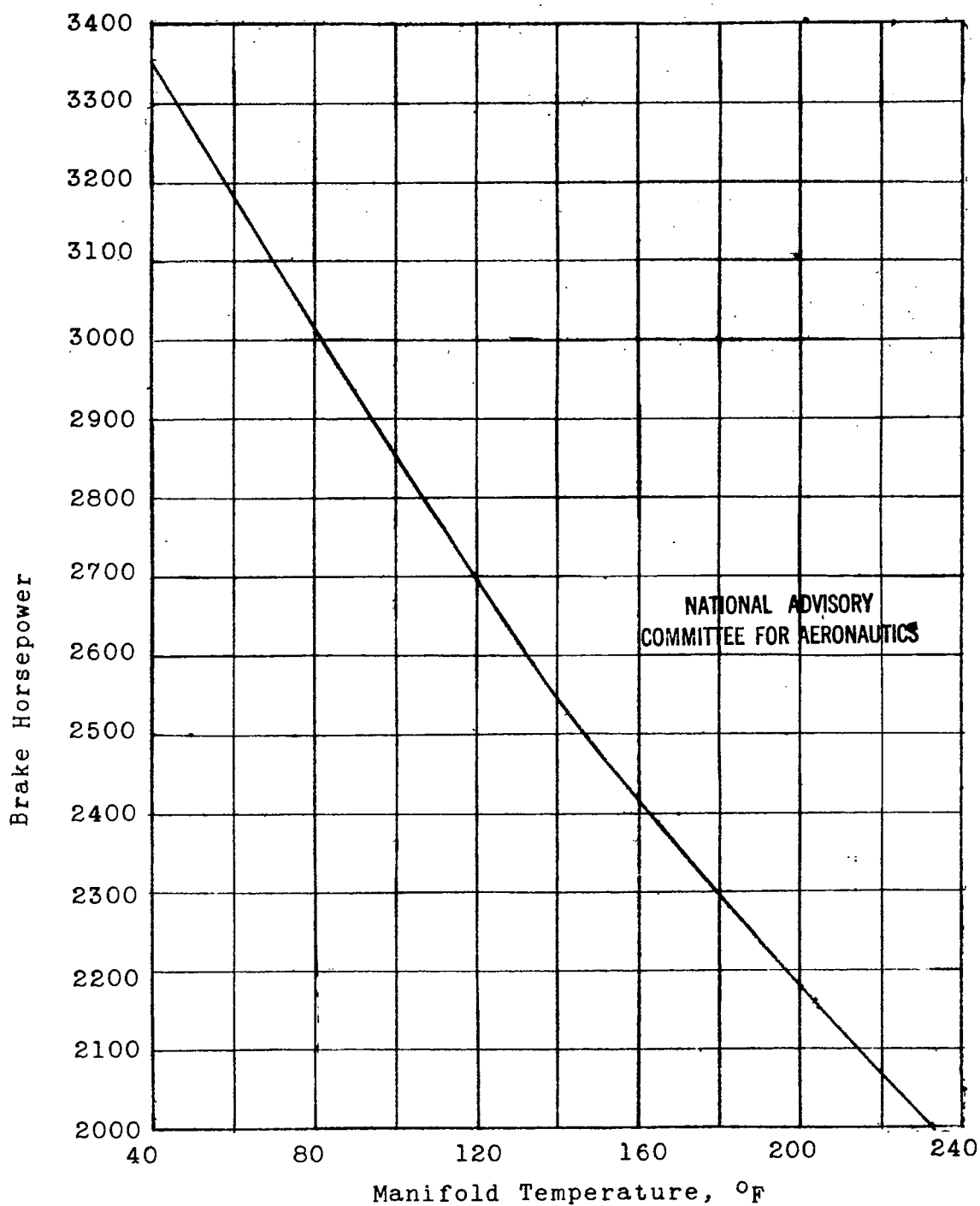


Figure 9.- Brake horsepower as a function of manifold temperature. Detonation-limited manifold pressure.

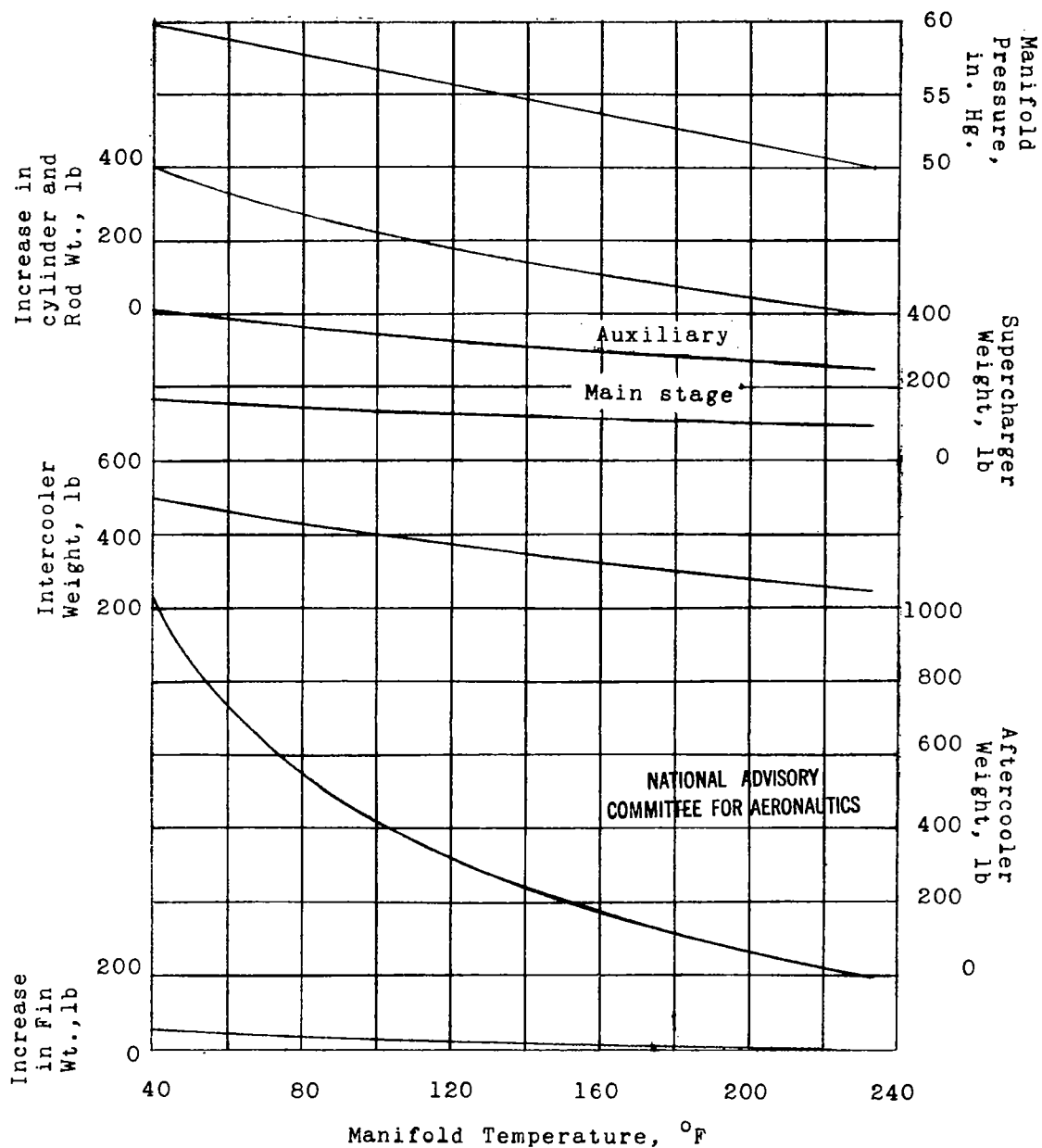


Figure 10.- Effect of manifold temperature on manifold pressure and required weight of various power-plant components. Detonation-limited manifold pressure.

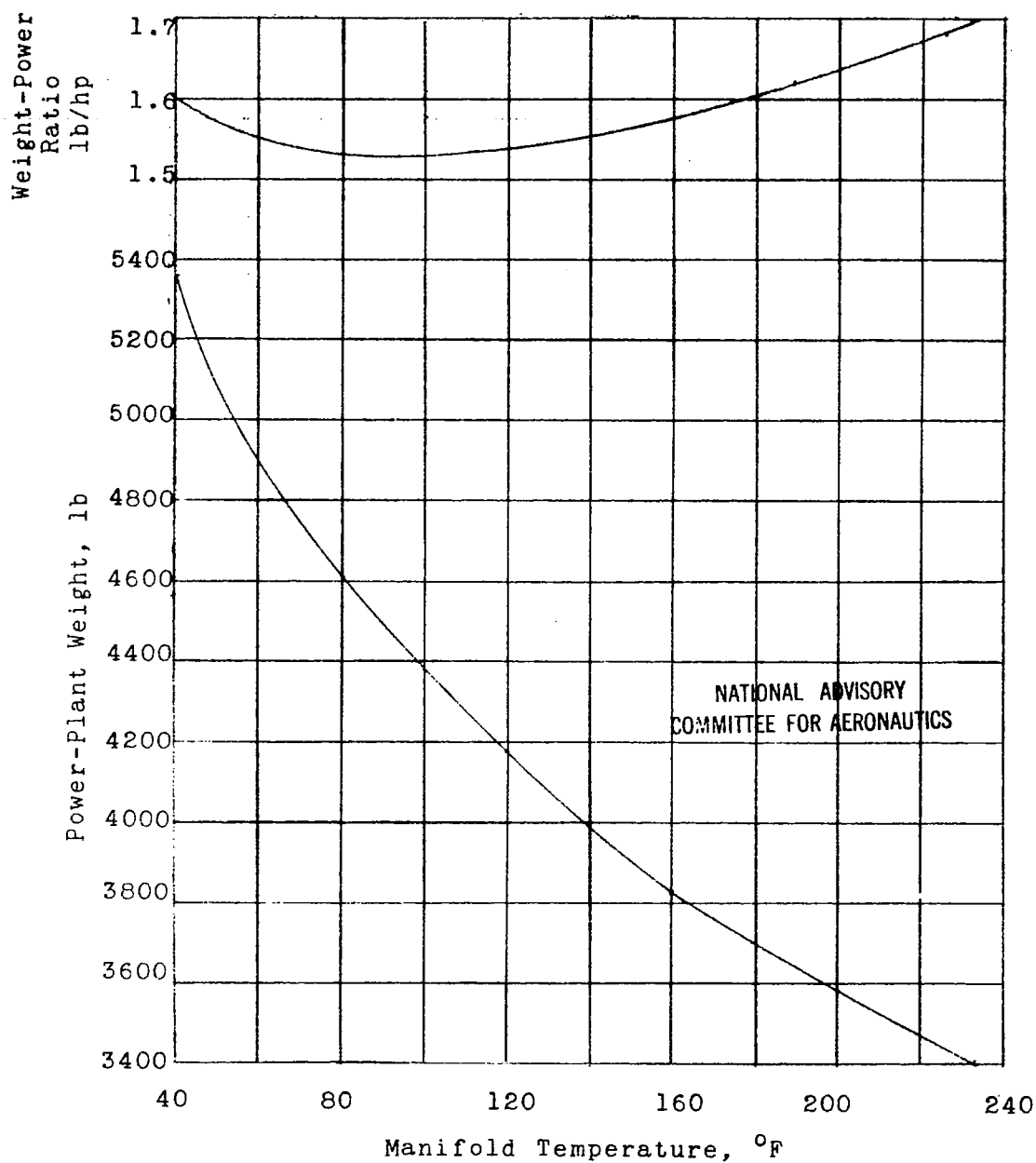


Figure 11.- Power-plant weight and weight-power ratio as functions of manifold temperature. Detonation-limited manifold pressure.

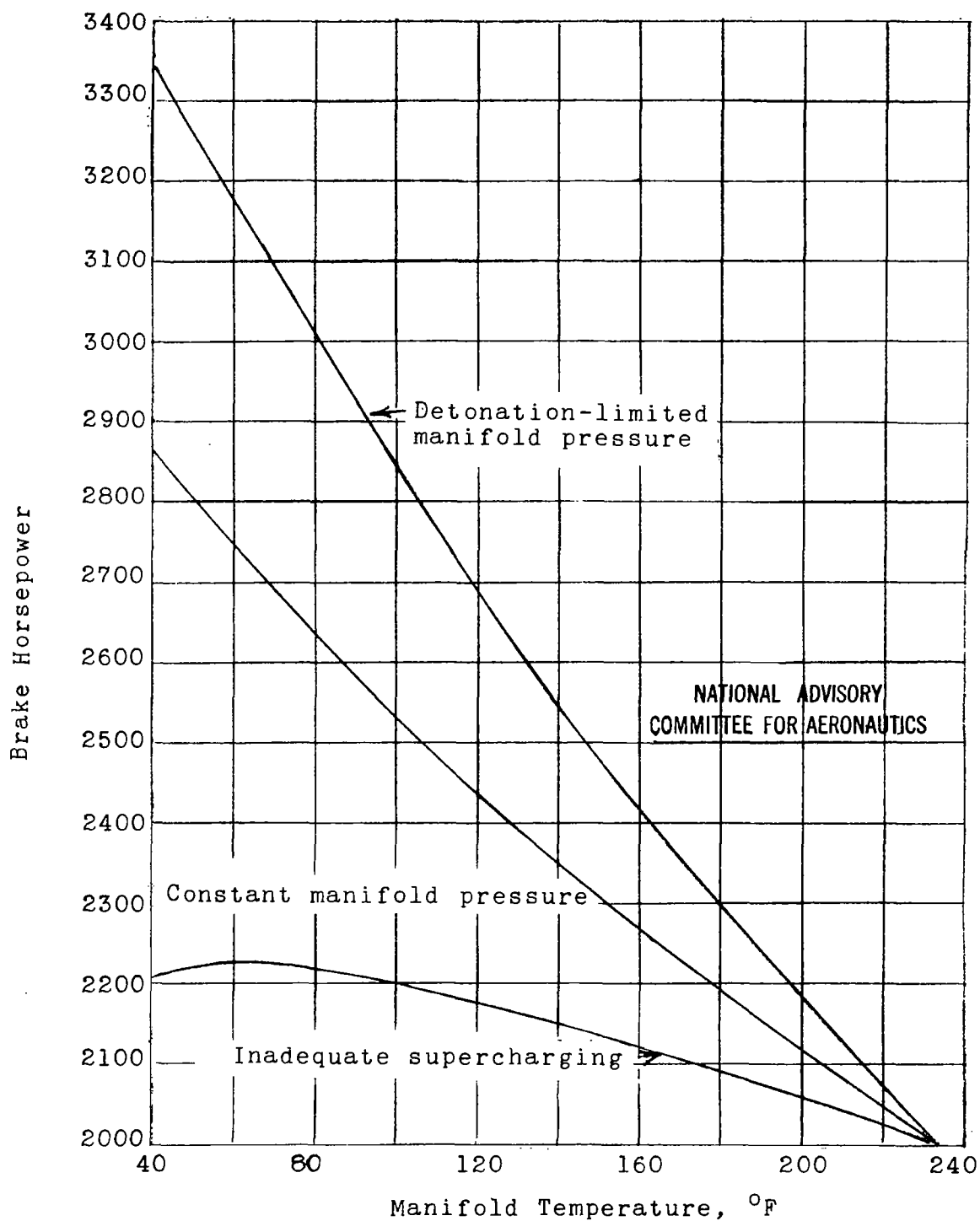


Figure 12.- Variation of brake horsepower with manifold temperature and supercharger performance.

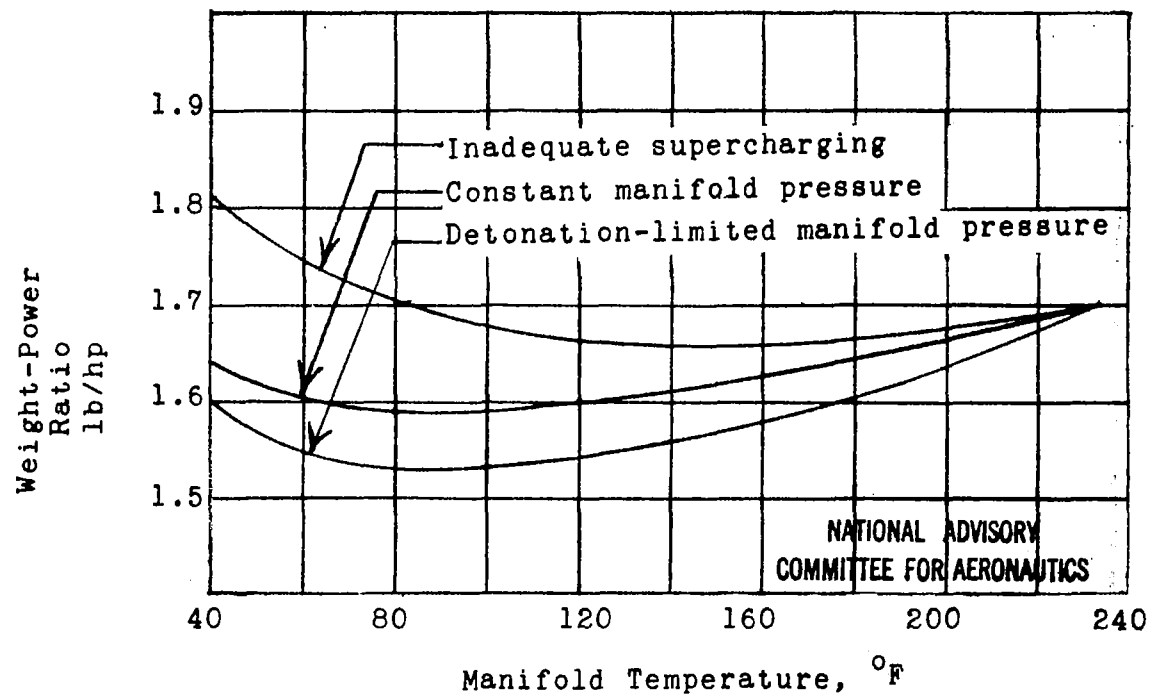


Figure 13.- Variation of power-plant weight-power ratio with manifold temperature and supercharger performance.

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